



ORIGINAL RESEARCH PAPER

An extensive inventory of municipal open waste burning nationwide based on machine learning analysis**B.S. Ramadan¹, S. Sendari², B. Ratnawati³, A.D. Sakti⁴, A.T. Balasbaneh⁵, M.A. Budiwardjo⁶, T. Matsumoto⁷, A.S. Puspita⁶**¹Department of Environmental Engineering, Faculty of Engineering, Universitas Diponegoro, Semarang, Indonesia²Department of Electrical Engineering, Universitas Negeri Malang, Jl. Semarang No. 5, Malang, Indonesia³Program Study of Engineering and Environmental Management, College of Vocational Studies, Institut Pertanian Bogor, 16151, Indonesia⁴Geographic Information Sciences and Technology Research Group, Faculty of Earth Sciences and Technology, Institut Teknologi Bandung, Bandung 40132, Indonesia⁵Sustainable Business School, London South Bank University, 103 Borough Road, London SE1 0AA, United Kingdom⁶Environmental Sustainability Research Group, Department of Environmental Engineering, Faculty of Engineering, Universitas Diponegoro, Semarang, 50275 Indonesia⁷Carbon Neutrality Promotion Division, Institute of Environmental Science and Technology, The University of Kitakyushu, Kitakyushu City, 808-0135 Japan**ARTICLE INFO****Article History:**

Received 20 October 2025

Revised 24 January 2026

Accepted 28 February 2026

Keywords:

Climate impacts

Emission inventory machine

learning analysis

Open waste burning

Waste management

ABSTRACT**BACKGROUND AND OBJECTIVES:** Residential open waste burning remains a major environmental and climate challenge in Indonesia. The study objectives were to conduct a comprehensive nationwide assessment of open burning by measuring its prevalence, recognizing spatial patterns, examining material composition, and revealing the behavioral influences that contribute to it. The ultimate objectives of this study were to generate evidence-based insights that can inform targeted policies and interventions to reduce open waste burning and its associated impacts.**METHODS:** The study integrates multiple approaches, including national datasets, a large-scale household survey, spatial analysis, and topic modelling of qualitative responses. The estimation of waste burning activities was conducted through a framework derived from the Intergovernmental Panel on Climate Change's activity and emission inventory, with a crucial improvement that integrated the official administrative classifications of Indonesian villages and cities to more precisely allocate uncollected waste fractions at the subnational level. Primary data were collected via an online questionnaire, yielding 722 valid responses distributed across major regional clusters in Indonesia, including Java, Sumatra, Kalimantan, Sulawesi, Bali-Nusa Tenggara, and eastern regions, characterizing household waste generation, disposal practices, and behavioral drivers.**FINDINGS:** The results indicate that in the reference year, approximately 26.6 million tonnes of municipal waste were estimated to be openly burned in Indonesia, corresponding to about 23.3 million tonnes of carbon dioxide equivalent emissions. Residential combustion represents approximately 70 percent of the overall waste incinerated, significantly surpassing the contributions from landfill fires. Spatial analysis revealed strong clustering of open waste burning in densely populated provinces, particularly on Java Island, with notable intra-provincial variation at the district level. Analysis of material composition revealed that dry and combustible components, including plastics, paper, wood, and garden waste, were disproportionately present in the incinerated waste. Latent Dirichlet Allocation topic modelling identified inadequate waste collection infrastructure and household convenience as dominant drivers of open burning.**CONCLUSION:** This study illustrates that open burning is a prevalent and serious concern in Indonesia, leading to considerable climate and environmental consequences. Given that residential burning constitutes approximately 70% of the 26.6 million tonnes incinerated annually, targeted improvements in household waste collection services present significant opportunities to decrease emissions.

DOI: 10.22034.gjesm.2026.02.14

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NUMBER OF REFERENCES

31

NUMBER OF FIGURES

6

NUMBER OF TABLES

6

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INTRODUCTION

Municipal solid waste management remains a persistent challenge in many low- and middle-income countries, particularly where rapid urbanization, population growth, and infrastructure development are not well-aligned (Haregu *et al.*, 2017). Over the last decade, waste generation in Indonesia has grown considerably, whereas the systems for waste collection and treatment continue to grapple with challenges regarding coverage, capacity, and affordability in the realm of waste management (Middha and Horne, 2024; Fatimah *et al.*, 2020). Consequently, a significant fraction of municipal waste is managed outside formal systems, leading to environmentally harmful practices such as uncontrolled dumping and open waste burning (OWB) at the household and community levels (Chavan *et al.*, 2022). Residential OWB are of particular concern because of their contribution to local air pollution, human health risks, and climate change. The uncontrolled incineration of various household refuse discharges particulate matter, toxic substances, and greenhouse gases, which encompass short-lived climate pollutants like black carbon (Mathew *et al.*, 2024). Although exposure to pollutants such as particulate matter is widely associated with respiratory and other adverse health outcomes, this study focuses on emission quantification and climate impact indicators at the national scale and does not conduct a detailed human health exposure or risk assessment. The broader literature acknowledges the potential disproportionate effects on vulnerable groups, including children and the elderly; however, this study did not conduct a specific evaluation of these impacts. Despite national regulations prohibiting open burning and policy commitments to improve waste management performance, OWB remains widely practiced, especially in areas with limited waste collection services. Consequently, comprehending the extent, spatial arrangement, and fundamental factors influencing residential OWB is essential for

formulating effective mitigation strategies and advancing national environmental and climate objectives (Ogut *et al.*, 2024). Previous studies have attempted to quantify waste-burning activities and their emissions on global, regional, and national scales. The Intergovernmental Panel on Climate Change (IPCC) provides methodological guidance for estimating emissions from OWB, forming the basis of many national inventories. Global and regional evaluations have underscored that the burning of residential and informal waste can represent a significant, albeit frequently overlooked, contributor to air pollutants and climate-forcing emissions (Ramadan *et al.*, 2022a; Velis *et al.*, 2021). In Indonesia and Southeast Asia, several studies have documented the prevalence of OWB and their environmental impacts (Ramadan *et al.*, 2025; Wiedinmyer *et al.*, 2014). Research has shown that OWB is closely linked to inadequate waste collection coverage, informal settlement patterns and limited access to waste treatment facilities. Recent studies based on inventory data have improved emission estimates by incorporating waste composition, combustible fractions, and refined activity data, illustrating that emissions from residential burning can overshadow those from landfill fires at the national level (Jakhar *et al.*, 2023; Ramadan *et al.*, 2023). Although this study builds upon the inventory framework of Ramadan *et al.* (2025), it quantitatively differs by reallocating uncollected waste fractions using official village–city classifications, incorporating updated national datasets for improved subnational emission estimates, and integrating household survey data to link spatial patterns with behavioral drivers. Nevertheless, a significant number of current studies depend heavily on generalized assumptions regarding the characteristics of rural and urban areas, uniform waste collection efficiencies, and proxy indicators for household behavior (Chaudhary *et al.*, 2021; Wiedinmyer *et al.*, 2014). While several national case studies have assessed open

waste burning and its emissions (Wiedinmyer *et al.*, 2014), most focus primarily on activity data and emission estimation (Chaudhary *et al.*, 2022; Thompson *et al.*, 2024). Consequently, there is limited empirical evidence linking national-scale emission estimates with household decision-making processes and perceived constraints. This study advances the current body of knowledge in several ways. Furthermore, it is significant to highlight that existing national inventory infrequently incorporate classifications of subnational administrative settlements to improve activity data. They also fail to consistently merge emission modeling with empirically obtained behavioral evidence to explain spatial heterogeneity. As a result, the methodological linkage between inventory refinement and household-level drivers remains insufficiently developed. Unlike general rural–urban categories that are usually based only on population density, the official village–city (*desa–kota*, in local language) classification reflects administrative status and how public services are managed. This difference is important because waste collection coverage, infrastructure development, and local enforcement are organized according to administrative areas. Through the application of official village and city classifications, this study optimizes the distribution of uncollected waste fractions and mitigates potential bias in subnational emission estimates. First, it refines existing waste burning inventory approaches by integrating official village–city classifications from the Indonesian Statistical Agency (BPS), allowing for a more accurate representation of settlement characteristics and waste collection conditions than conventional rural–urban assumptions. Second, this study combined national datasets with primary household survey data from 722 valid respondents, enabling triangulation between top-down statistics and bottom-up behavioral evidence. Third, machine learning–based topic modelling as latent dirichlet allocation (LDA) was

applied to systematically identify the dominant reasons behind residential OWB practices and the strategies perceived by households as most effective for reducing OWB. This strategy goes beyond simple descriptive surveys by uncovering latent themes within open-ended responses, thus delivering a data-informed comprehension of the behavioral and institutional drivers. Finally, by linking spatially explicit waste burning estimates with climate impact indicators, this study offers an integrated perspective that connects household behavior, regional waste management performance, and emission outcomes. The primary aim of this study was to quantify, spatially characterize, and explain residential OWB practices in Indonesia, with a focus on identifying effective pathways for mitigation. This study is formulated as a national cross-sectional analysis grounded in the most up-to-date consolidated datasets and does not intend to examine temporal trends in OWB over an extended period. The analysis is based on aggregated annual data and does not explicitly assess potential seasonal variations in OWB activities, such as differences between dry and rainy seasons. The primary objective of this study is to 1) evaluate the burning activities associated with residential and landfill waste at the provincial and sub-provincial levels, employing a revised activity and emission inventory framework; 2) assess the spatial distribution and climate impact of waste burning across Indonesia; 3) characterize household waste generation, disposal practices, and infrastructure availability based on a large-scale questionnaire survey; and 4) determine the primary factors influencing residential OWB and explore possible mitigation strategies using topic modelling of open-ended survey responses. By achieving these objectives, this study aims to provide evidence-based insights to support more targeted waste management interventions and policy actions to reduce OWB and its associated environmental and climate impacts. This study was conducted in Indonesia in 2025.

MATERIALS AND METHODS

Study context and data sources

This study uses national waste management datasets as input parameters for emission inventory calculations. Data were obtained primarily from the National Waste Management Information System (SIPSN) operated by the Ministry of Environment and Forestry, as well as from the Indonesian Statistical Agency (BPS). National waste generation is reported to range from 19 to 60 million tons annually, depending on the coverage of reporting and the year in question, with management rates falling between roughly 34–39 percent (%). For the reference year 2023, SIPSN records indicate total waste generation of 56.6 Mt, of which about 39% was formally managed. These figures underscore that despite regulatory frameworks, such as the Presidential Regulation on national waste management targets, which aim for significantly higher management rates (70%), implementation remains incomplete. In the context of waste composition, the SIPSN categorization reveals that organic waste, encompassing food and backyard waste, accounts for the predominant share of the Indonesian waste stream, often noted to be around 40% or more. This is succeeded by plastics and other components, reflecting standard household and market waste patterns. This composition profile has direct implications for waste-handling strategies, as a high organic content suggests opportunities for composting and valorisation, whereas significant plastic and mixed fractions present ongoing challenges for recycling systems. Despite considerable production volumes and evolving infrastructure (for instances, landfill facilities, reduce reuse recycle facilities, and waste banks), the observed pace of scaling and integration into municipal systems is uneven across regions, indicating the continued need for policy emphasis on service expansion, segregation at source, and resource recovery pathways.

Data collection

Data collection in this study combined a literature survey compilation and an online survey to comprehensively characterize waste-related conditions in Indonesia. The literature and database review followed a structured search strategy. Official datasets were identified through systematic screening of national statistical portals (BPS and SIPSN), while supporting academic references were selected using keyword combinations such as “open waste burning”, “municipal solid waste Indonesia”, and “emission inventory OWB” in major scientific databases. Only peer-reviewed articles, official government statistics, and reports published between 2010–2025 were included. Sources lacking methodological transparency or national relevance were excluded. The literature survey data were acquired through a methodical review of literature and databases, leveraging official statistics from the Indonesian Statistical Agency (BPS), SIPSN, and regional gross rate domestic product (GRDP) databases to capture spatial, demographic, socio-economic, and waste management indicators at the regency and city levels. The data presented established the basis for evaluating waste generation, management efficiency, waste composition, and related derived indicators through computational methods. In parallel, primary data were collected through an online questionnaire survey designed to capture household-level waste generation characteristics, waste management practices, infrastructure availability, and contextual perceptions. The structure of the questionnaire adhered to a predetermined design that included eligibility screening, respondent profiling, household waste characteristics, management practices, and perceptions related to policy. It was implemented through a cluster-based regional approach. The integration of national datasets and primary survey data enabled triangulation between national-level waste statistics and household-scale conditions, strengthening the robustness of

the analysis. Discrepancies in the totals reported by SIPSN (for instance, 19.3 Mt compared to 56.6 Mt) indicate differences in the extent of reporting across various regencies and cities, as well as the completeness of data for each year. For emission estimation, the study consistently uses the consolidated 2023 national dataset (56.6 Mt) to ensure comparability. For regencies not fully covered in SIPSN reporting, waste generation values were approximated using population-based extrapolation derived from BPS demographic statistics and regional per capita waste generation rates.

Data collection for OWB profiling

All emission estimates in this study refer to the reference year 2023, based on the most recent consolidated national datasets available at the time of analysis. [Table 1](#) outlines the data sources employed to evaluate waste-related activities throughout the administrative regions in Indonesia. Spatial and administrative variables, including regency and city names, land area, population, and the number of villages and cities, were primarily derived from official statistics published by the Indonesian Statistical Agency (BPS). These datasets present the crucial geographical and demographic structure needed to delineate regional disparities and to assist in further calculations. Indicators such as population density and the proportion of villages to cities were derived through calculations based on the original statistical data. Socio-economic indicators, particularly GRDP at constant prices (2022), were obtained from regional GRDP databases to represent economic conditions that may influence waste generation and management performance. The GRDP was not explicitly factored into the equations used for emission calculations. Rather, it served as a contextual reference to understand regional disparities in waste generation and management performance in the discussion section. These socio-economic variables, including regional economic indicators, education level, and urban–rural classification,

were used for descriptive and contextual interpretation. Nevertheless, the research does not conduct inferential statistical modeling to measure causal connections between socioeconomic factors and practices related to open waste burning. Waste generation data, including total annual waste generation and waste management or collection efficiency, were sourced from the SIPSN website. Per capita waste generation rates were subsequently calculated using population data, enabling comparability across regions with different population sizes. Additional parameters relevant to waste flow characterization were estimated through a combination of reported data and calculated assumptions. The fraction of uncollected waste ($f_{uncollected}$) was calculated as 1 minus the reported waste collection or management efficiency for each administrative unit based on SIPSN data. In regions where comprehensive reporting is absent, values were approximated by utilizing population-weighted averages within the corresponding regional cluster. The combustible fraction (B_{frac}) was derived from reported waste composition data by summing combustible components (e.g., plastics, paper, textiles, wood, and yard waste) and excluding inert fractions such as metals and glass. These include the fraction of uncollected waste, detailed waste composition fractions, and the combustible portion of municipal solid waste. The emission factors utilized in the following analyses were derived from reputable literature sources to guarantee methodological consistency and comparability with previous studies. The emission factors from [Ramadan et al. \(2025\)](#) are IPCC-aligned and represent typical uncontrolled mixed municipal waste burning conditions. Uniform factors were applied across provinces to ensure national comparability and methodological consistency. Collectively, these datasets offer a cohesive foundation for evaluating regional waste management circumstances and facilitating quantitative analysis of waste-related endeavors at both national and subnational levels.

Table 1: Data sources for estimated waste burned activity

Data	Sources
Name	Statistical Agency data per province 2023
Area (kilometer squares/km ²)	Statistical Agency data per province 2023
Population (people)	Statistical Agency data per province 2023
Number of villages by administration	Village and city classification data, Statistical Agency 2020
Number of cities by administration	Village and city classification data, Statistical Agency 2020
Percentage of villages to cities by administration	Calculation
Number of villages	Village and city classification data, population data per village, Statistical Agency 2020
Number of cities	Village and city classification data, population data per village, Statistical Agency 2020
Percentage of villages to cities	Calculation
Regional density (people/km ²)	Calculation
GRDP at constant prices (2022) (Rupiah/Rp)	GRDP Data
Waste generation in 2022 (t/y)	SIPSN website
Waste generation per capita (kilogram per day (kg/d))	Calculation
Waste collection/management efficiency (%)	SIPSN website, Waste management percentage
Fraction of uncollected waste (%)	Calculation
Fraction of waste composition (%)	SIPSN website
Combustible waste (%)	Calculation
Emission factors	Ramadan et al. (2025)

Questionnaire design and sampling method

This study employed a cross-sectional questionnaire survey administered online to capture household-level waste management conditions and perceptions in Indonesia. The online-only approach may introduce socio-economic bias, as participation requires internet access and digital literacy; this limitation is acknowledged in the interpretation of results. The questionnaire was formulated based on a systematic design that encompasses respondent eligibility, socio-demographic characteristics, household waste generation and composition, waste management practices, availability of community waste infrastructure, awareness of waste-related programs, and the challenges and solutions perceived by respondents. Prior to full deployment, the questionnaire structure and wording were reviewed internally and pilot-tested to ensure clarity and logical flow. Internal consistency of key multi-item sections was assessed using Cronbach's alpha, indicating acceptable reliability. The concluding instrument integrated closed-ended questions for quantitative assessment along with chosen open-ended questions to obtain contextual

explanations and qualitative insights. Although the questionnaire assessed the availability of formal waste infrastructure such as waste banks and material recovery facilities (MRFs), it did not explicitly collect quantitative information regarding the role of informal recycling activities or waste pickers in influencing household decisions to burn waste. Therefore, the potential influence of informal recycling networks is discussed indirectly through reported waste management practices rather than through direct measurement. Furthermore, the questionnaire gathered data on various on alternative waste management practices reported by households, including composting, recycling, and formal collection services. Nevertheless, the study did not perform a comprehensive technical or economic feasibility assessment of alternatives such as composting systems, incineration with energy recovery, or recycling adoption potential; these were evaluated descriptively relying on reported practices and perceived preferences rather than through quantitative feasibility modelling. Perceived constraints, including high transportation costs and limited access to collection services, were captured in the survey

and interpreted as structural factors influencing household waste management decisions. Questionnaire design can be seen in [Table 2](#). Data gathering was executed utilizing an online survey platform, yielding a total of 1,025 responses. To mitigate duplicate submissions, the survey platform restricted multiple entries from the same device/IP and responses were screened for identical patterns. To ensure analytical relevance, a multi-stage screening process was applied. First, respondents who reported never observing or engaging in open waste burning were excluded from the behavioral driver analysis. Nonetheless, these responses were preserved within the larger dataset and were not utilized to exaggerate national prevalence estimates. Second, responses with substantial missing data, inconsistent answers, or incomplete key sections were removed. Following this filtering process, 722 questionnaires were deemed valid and retained for further analysis, representing approximately 70.4 % of the total collected responses. To account for Indonesia's geographical diversity, the survey sample was clustered by region following the predefined clustering framework outlined in the study protocol. Participants were categorized into significant regional clusters/ islands (for instance, Java, Sumatra, Kalimantan, Sulawesi, Bali–Nusa Tenggara, and Maluku–Papua), facilitating equitable representation and comparative analysis across regions. This cluster-based methodology allowed for the detection of spatial disparities in the characteristics of household waste generation, the accessibility of services, and the practices of waste management, while also preserving a sufficient sample size within each cluster for analysis. No formal power calculation was conducted, as the study was designed for descriptive and exploratory analysis rather than inferential hypothesis testing. As the questionnaire was administered online, households without stable internet access or sufficient digital literacy may have been less likely to participate, particularly in remote or rural areas. Despite attempts to disseminate the survey

throughout various regional clusters, the sample may not completely reflect populations with restricted connectivity. This limitation should be considered when interpreting the survey-based findings. Participation was voluntary, informed consent was obtained at the beginning of the survey, and no personal identifiers were collected.

Data analysis

The quantitative survey data were analyzed using descriptive statistical methods, including frequency distributions, percentage calculations, and regional comparisons based on predefined clusters. No inferential statistical tests or regression modelling were utilized, since the objective of the study was to describe patterns rather than test causal hypotheses. Spatial and material composition data were processed through aggregated calculations at provincial and subnational levels. Qualitative responses were analysed using Latent Dirichlet Allocation (LDA) as described below. The study did not aim to determine statistically significant relationships among variables; instead, its robustness was reinforced through triangulation between national datasets and primary survey responses, consistency with established inventory methodologies, and systematic validation steps within the topic modelling process (for instance, topic coherence evaluation and multidimensional scaling stress assessment). This approach ensures analytical transparency while aligning with the descriptive and inventory-based objectives of the study. No formal uncertainty propagation such as, Monte Carlo simulation was performed. Waste generation, collection efficiency, and emission factors were treated as deterministic inputs; therefore, combined uncertainty ranges were not calculated. The findings represent central inventory estimates rather than outputs based on probability. The village–city classification assumes homogeneity within each administrative category. The gradients found in peri-urban areas and the variability within categories were not modeled in detail, potentially resulting in a simplification of

Table 2: Questionnaire design

Section	Objective	Key Variables / Indicators	Question Type	Measurement Scale / Response Options
Pre-screening	Identify eligible respondents who have exposure to open burning of household waste	Experience observing open burning; experience practicing open burning	Closed-ended	Nominal (Yes / No / Do not know)
Respondent Profile	Capture socio-demographic characteristics of respondents	Age; gender; education level; occupation; household head status; place of origin and current domicile	Closed-ended	Nominal and ordinal categories
Household Characteristics	Describe household context related to waste generation	Household size (number of residents)	Closed-ended	Discrete numerical
Waste Generation	Estimate household waste quantity	Daily waste generation per household	Closed-ended (estimation)	Ordinal (volume categories in liters / bag size equivalents)
Waste Composition	Characterize types of household waste generated	Food waste; garden waste; paper; plastics (soft & rigid); textiles; glass; metals; hazardous waste; nappies; residue	Closed-ended	Percentage distribution (%); zero value allowed ("not available")
Waste Management Practices	Identify existing waste handling and disposal methods	Waste collection by private/DLH services; open burning; dumping; burial; composting; others	Closed-ended (multiple choice)	Nominal
Uncollected Waste Handling	Understand coping strategies when collection services are absent	Alternative waste disposal methods	Closed-ended	Nominal
Waste Infrastructure Availability	Assess access to community-based waste facilities	Presence of waste bank; presence of MRF	Closed-ended	Nominal (Yes / No / Do not know)
Awareness & Capacity Building	Measure exposure to waste-related education and outreach	Participation in socialization, training, or awareness activities	Closed-ended	Nominal (Yes / No)
Perceived Impacts of Open Burning	Explore perceived positive and negative impacts of open burning	Environmental, health, economic, and practical impacts	Open-ended	Qualitative (thematic analysis)
Regulatory Awareness	Assess awareness of legal restrictions on open burning	Knowledge of existing regulations	Closed-ended	Nominal (Yes / No / Do not know)
Drivers of Open Burning	Identify structural and socio-economic drivers	High transport costs; lack of collection services; cultural practices; other reasons	Mixed (closed-ended with explanation)	Nominal + short qualitative justification
Persistence Factors	Explore additional motivations sustaining open burning practices	Other underlying or contextual reasons	Open-ended	Qualitative
Policy & Management Recommendations	Capture community-based solutions and expectations	Preferred waste management methods; suggested strategies and interventions	Open-ended	Qualitative

spatial data. Double counting between residential burning (W_{Bres}) and disposal-site burning (W_{Bdump}) was avoided by separating uncollected waste fractions (allocated to W_{Bres}) from collected waste fractions subject to disposal-site burning (allocated to W_{Bdump}). Carbon dioxide (CO_2) equivalent values were calculated using 100-year global warming potential (GWP100) values consistent with IPCC AR6 recommendations. The findings related to spatial clustering are presented in a descriptive manner; formal spatial

autocorrelation metrics (for instance, Moran's I) were not employed, as the focus of the analysis was on the spatial distribution derived from inventory rather than statistical spatial inference. Independent atmospheric measurements or field-based validation data were not available; validation was conducted through methodological consistency with IPCC guidelines and comparison with published national inventory studies. The allocation of uncollected waste to open burning follows established inventory practice; however,

only the combustible fraction is assumed to be burned, not the entire uncollected amount. The evaluation is fixed and restricted to the reference year 2023. Temporal dynamics and interannual variability were not assessed.

Activity and emission profile of municipal OWB in Indonesia

The estimation of waste burning activity and associated emissions in this study followed the updated activity inventory methods and emission inventory framework developed by [Ramadan et al. \(2025\)](#), which are based on refinements of the 2006 IPCC Guidelines for OWB. The methodological framework, which encompasses the distinction between residential burning and incineration at disposal sites, the utilization of uncollected waste fractions, and the implementation of pollutant-specific emission factors, was preserved to maintain consistency and comparability with both regional and international inventories. However, a key modification was introduced in the determination of settlement characteristics, where the distinction between villages and cities was defined explicitly using official Indonesian administrative classifications from the Statistical Agency report rather than relying solely on generic rural–urban assumptions. In this study, residential waste burning was estimated by differentiating waste generation and collection characteristics between villages (*desa*) and cities (*kota*). Villages were assumed to have lower collection coverage and higher likelihood of unmanaged waste disposal, while cities were characterized by higher, but still incomplete, collection services. This categorization enabled a more precise assignment of uncollected waste fractions at the subnational level. Waste burning at disposal sites (WB_{dump}) was estimated assuming that uncontrolled dumping and associated burning primarily occur at formal or semi-formal disposal facilities, which are predominantly located in urban administrative

areas according to national waste infrastructure distribution data. Greenhouse gas emissions, short-lived climate pollutants, and various primary air pollutants were assessed by taking the total waste burning (WB) and multiplying it by the emission factors specific to each pollutant, as well as the combustible fraction of municipal solid waste, following the emission inventory equations established by [Ramadan et al. \(2025\)](#) (Table 3). Sensitivity is expected to be most influenced by assumptions on uncollected waste fractions and the selected emission factors, which are highlighted as key sources of variability. By explicitly incorporating village–city characteristics based on BPS data, this approach reduces potential overestimation associated with uniform rural–urban assumptions and provides a more context-sensitive representation of waste burning activities in Indonesia. Like all emission estimates based on inventory, the findings are influenced by uncertainties related to activity data, emission factors, and assumptions concerning uncollected waste fractions. Potential underreporting or unobserved small-scale burning activities cannot be entirely excluded. However, the methodology relies on established IPCC-based inventory frameworks and nationally aggregated datasets rather than solely on self-reported burning behavior, which enhances the robustness and comparability of the estimates. This study did not include a formal uncertainty propagation analysis, for instance, confidence intervals. The reported emission values therefore represent deterministic central estimates based on the best available national datasets and literature-derived emission factors and should be interpreted accordingly. Accordingly, the reported values of 26.6 million tonnes of waste burned and 23.3 million tonnes CO₂ equivalent emissions should be interpreted as indicative national-scale estimates derived from standardized inventory procedures, rather than as exact measurements with quantified confidence intervals.

Table 3: Equations used in estimating emission

Parameter	Equations	Sources
The amount of MSW that was openly burned at the residential area	$W_{Bres} = MSW_p \times [(P_{rural} \times f_{uncollected(rural)}) + (P_{urban} \times f_{uncollected(urban)})] \times B_{frac}$	Ramadan et al., 2022a
The amount of MSW that was openly burned at the disposal site	$W_{Bdump} = MSW_p \times P_{urban} \times f_{collected(urban)} \times \lambda \times B_{frac}$	Wiedinmyer et al., 2014
Total MSW burned	$W_B = W_{Bres} + W_{Bdump}$	Ramadan et al., 2023
Total CO ₂ emissions	$Total\ CO_2\ Emissions\ (CO_{2T}) = W_B \times \sum_j (WF_j \times dm_j \times CF_j \times FCF_j) \times \frac{44}{12}$	Ramadan et al., 2025
Total CH ₄ , N ₂ O, BC, SO ₂ , PM ₁₀ , PM _{2.5} , CO, NO _x emissions	$Total\ x\ emissions = W_B \times EF_{CH_4} \times \delta$	Heston et al., 2023
Total climate impact BC, CH ₄ , N ₂ O	$Climate\ impact\ of\ x = x_T \times GWP_x$	Pathak et al., 2023

Text data analysis and topic modelling

To ascertain the fundamental causes of household waste incineration practices and to investigate possible strategies for their reduction, qualitative responses from the questionnaire were examined utilizing topic modeling techniques applied in the orange data mining software (Fig. 1). Open-ended responses related to motivations for waste burning and suggested mitigation strategies were first compiled into a structured text corpus by exporting responses into a comma-separated values (CSV) format. This corpus was subsequently imported into orange for text processing and analysis. Prior to modelling, the text data underwent a standardized preprocessing workflow, including tokenization, conversion to lowercase, removal of punctuation and numerical characters, stop-word elimination, and lemmatization to reduce words to their base forms (Table 4). These measures were implemented to enhance semantic coherence and minimize noise within the textual dataset. The cleaned corpus was then used as the input for Latent Dirichlet Allocation (Heston et al., 2023), an unsupervised probabilistic topic modelling method that identifies latent thematic structures based on word co-occurrence patterns across documents. The total number of topics was ascertained iteratively by evaluating both topic coherence and interpretability, which guaranteed that the derived topics effectively captured the main narratives found in the answers provided by

the respondents. Topic coherence (Cv) scores were calculated for models ranging from 3–10 topics, and the selected model showed the highest coherence score (Cv = 0.51), balancing interpretability and thematic separation. LDA assumes a bag-of-words representation and conditional independence between terms; these assumptions may simplify semantic structure but remain standard practice in exploratory topic modelling. The concluding corpus included 722 valid open-ended responses that served as separate documents within the LDA model. Model stability was assessed by running the LDA model multiple times with different random seeds; dominant topic structures remained consistent. Stop-word lists were based on the standard Indonesian language corpus available within the orange text-mining library, supplemented by manual removal of domain-irrelevant terms. All preprocessing and modelling were conducted in Indonesian. The topic was interpreted and reported in English after the modeling phase to mitigate any potential translation bias during computational analysis. To support interpretation and validation of the topic structure, latent Dirichlet allocation visualization (LDAvis) was employed to visualize topic saliency and term relevance, while multidimensional scaling (MDS) was used to map inter-topic distances in a two-dimensional space. The assessment of the MDS representation's quality was conducted through Kruskal's stress value, where values under 0.05

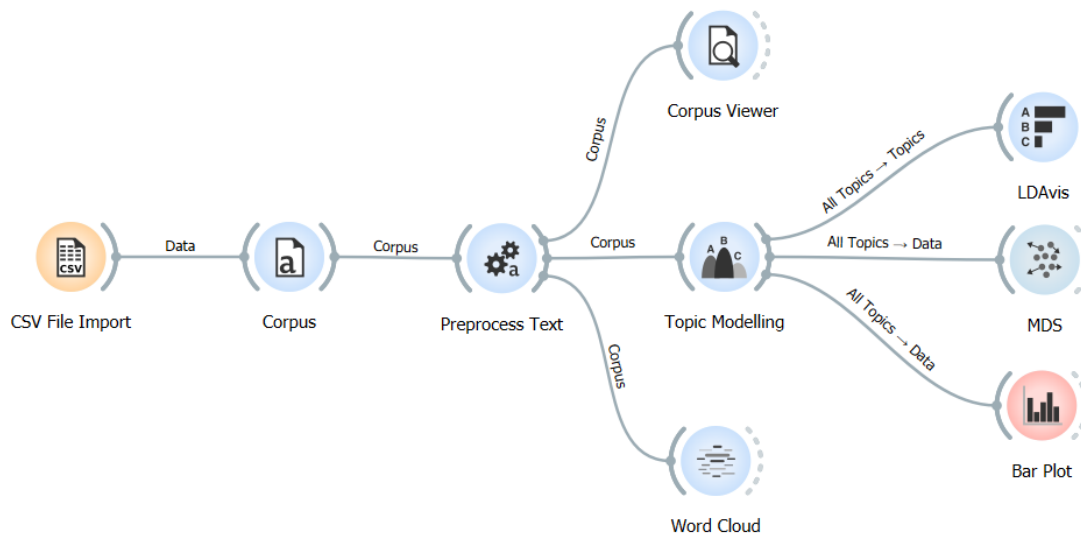


Fig. 1: Project workflow of text mining analysis

Table 4: Preprocessing criteria in the topic modelling

Data	Criteria
Transformation	<i>Lowercase</i> = Turning all text to lowercase <i>Parse html</i> = Parse out text only and remove html tags <i>Remove urls</i> = Remove all urls from text
Tokenization	<i>Word & Punctuation</i> = splitting the text by words and keep punctuations symbols
Filtering	<i>Stopwords</i> = Removing stopwords from the text and set the language to Indonesian (since the original text / Indonesian was used) <i>Numbers</i> = Numbers were not included in the corpus <i>Regex</i> = Splitting the text by providing some separation character

signify an outstanding low-dimensional fit and minimal distortion of inter-topic relationships (Keklik and Şahin, 2022). The resulting Kruskal's stress value was 0.032, indicating excellent low-dimensional representation. Supplementary visual representations, such as word clouds and frequency bar plots categorized by topic, were created to aid in the qualitative analysis of the predominant terms associated within each topic. Topic interpretation was independently reviewed by two researchers to reduce subjectivity, and discrepancies were resolved through discussion. The combined use of LDA, LDavis, and MDS enabled a robust identification of key behavioural drivers of waste burning and recurring themes in proposed mitigation strategies, grounded directly in respondents' narratives.

RESULTS AND DISCUSSION

Profile of waste burning activity in Indonesia

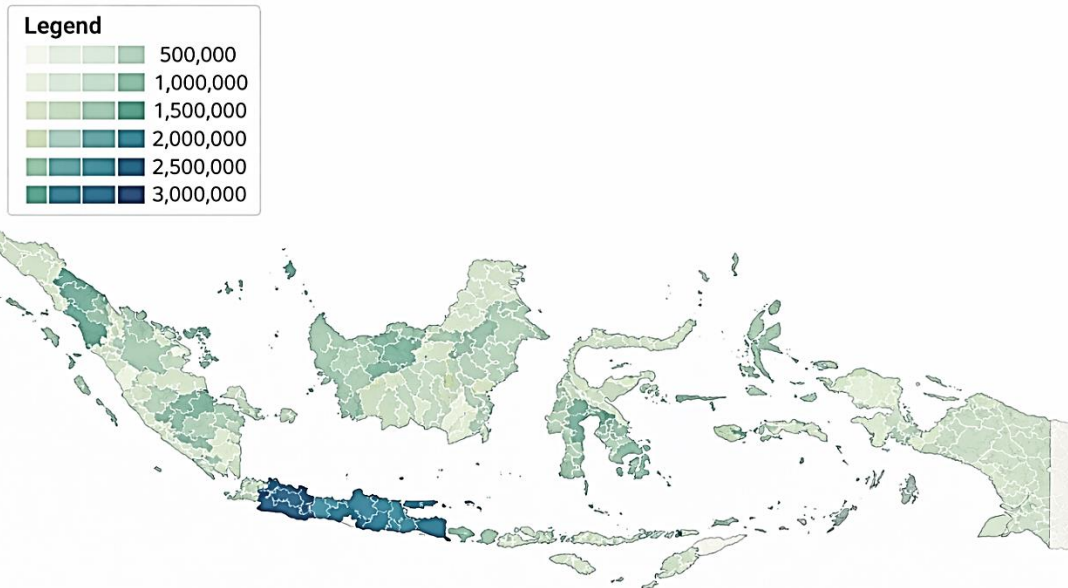
The provincial-level assessment indicates that waste burning in Indonesia amounts to approximately 26.64 Mt/y, generating a total climate impact of about 23.34 million tons carbon dioxide equivalent (MtCO₂e) annually. Of this total, residential waste burning (WB_{Res}) accounts for the dominant share (18.71 Mt/y; ~70 %), while landfill-related fires (WB_{dump}) contribute 7.93 Mt/y (~30 %). This verifies that practices at both the household and neighborhood levels continue to be the main contributors to waste burning across the country, although landfill fires serve as a significant secondary source in certain provinces. It should be noted that these pollutant and climate

impact values were not directly measured in the field. Emissions of CH₄, N₂O, black carbon (BC), particulate matter (PM), CO, NO_x, and SO₂ were estimated using established emission factors within an IPCC-based inventory framework. The analysis did not specifically quantify heavy metals that may be associated with the combustion of plastics. The spatial distribution is highly uneven, reflecting strong differences in population density, waste generation, and waste management infrastructure across regions. This study employs a descriptive, inventory-based methodology; consequently, the findings aim to illustrate spatial patterns instead of statistically examining causal factors. Provinces on Java Island overwhelmingly dominate the national waste burning profile. West Java alone contributes more than 5.12 Mt/y, corresponding to a climate impact of 4.49 MtCO_{2e}, making it the single largest contributor nationally. This is followed by East Java (3.41 Mt/y; 3.01 MtCO_{2e}) and Central Java (3.16 Mt/y; 2.78 MtCO_{2e}). Together, these three provinces account for nearly 44 % of Indonesia's total waste burned, underscoring the influence of large populations and high absolute waste generation. Therefore, the prevalence of Java must be understood in the context of demographic size and the intensity of waste generation, rather than merely as a sign of inadequate waste management performance. Banten (1.33 Mt/y) and DKI Jakarta present contrasting profiles: while Jakarta's total waste burned is relatively moderate (1.14 Mt/y), it is overwhelmingly dominated by landfill fires (>99% WB_{dump}), highlighting the role of large, centralized disposal sites rather than household burning in highly urbanized settings. Outside Java, waste burning levels are generally lower in absolute terms but remain environmentally significant. In Sumatra, provinces such as North Sumatra (1.55 Mt/y; 1.33 MtCO_{2e}), South Sumatra (0.89 Mt/y; 0.77 MtCO_{2e}), Lampung (0.89 Mt/y; 0.76 MtCO_{2e}), and Riau (0.79 Mt/y; 0.65 MtCO_{2e}) emerge as

regional hotspots. In these provinces, it is clear that residential burning is the dominant practice, although landfill fires also account for substantial contributions, particularly in North Sumatra and Riau. This pattern is consistent with areas where partial collection coverage coexists with continued reliance on informal disposal and household burning (Fig. 2). These associations illustrate the spatial patterns that have been observed and should not be construed as statistically confirmed causal relationships. In Kalimantan, Sulawesi, Bali–Nusa Tenggara, and eastern Indonesia, total waste burned per province is typically below 0.6 Mt/y, yet residential burning remains the principal pathway. Provinces such as South Sulawesi (0.85 Mt/y; 0.73 MtCO_{2e}) and Bali (0.56 Mt/y; 0.50 MtCO_{2e}) stand out due to relatively high tourism- or urban-driven waste generation combined with limited downstream treatment capacity. In contrast, provinces in Papua and Maluku show much lower absolute quantities (generally <0.15 Mt/y per province), with landfill fires playing only a minor role. In summary, the provincial profile indicates that the issue of waste burning in Indonesia is predominantly a residential matter, primarily concentrated in densely populated provinces, whereas landfill fires are particularly critical in major urban and metropolitan regions. This differentiation has important implications for mitigation strategies, indicating that household-level interventions are essential nationwide, while landfill fire prevention should be prioritized in selected high-burden provinces. Fig. 3 demonstrates a distinctly varied spatial pattern of municipal waste combustion across Indonesia, with notable concentrations in regions that are heavily populated and urbanized. The highest waste burning intensities (up to ~117 Mkg/year per administrative unit) are strongly concentrated along Java Island, particularly in metropolitan and peri-urban corridors spanning West Java, Central Java, East Java, and the Greater Jakarta region.

Residential Burning (t/y)

(a)



Landfill Fires (t/y)

(b)

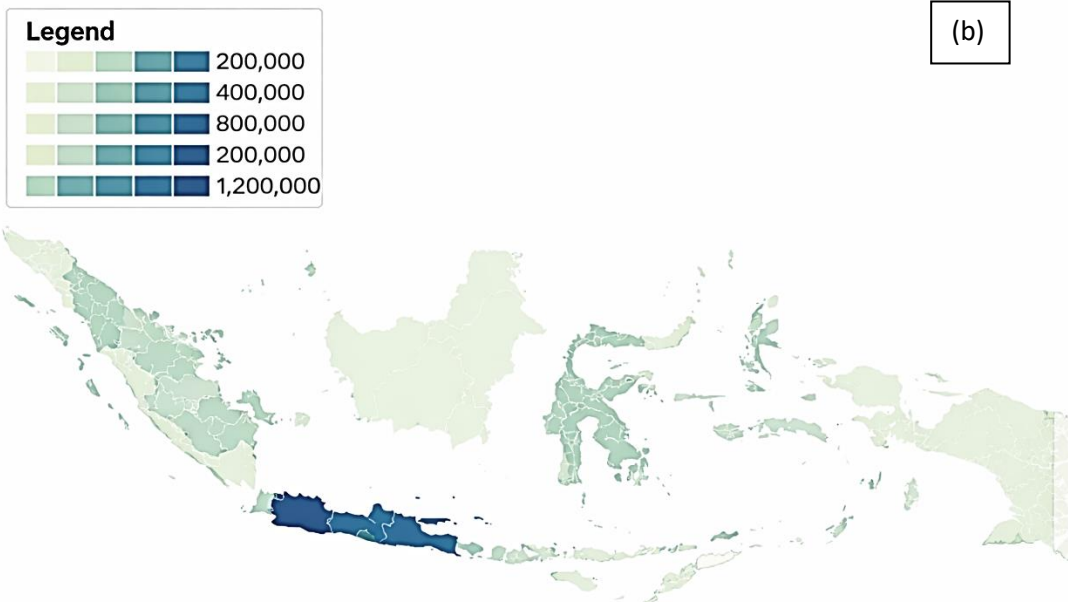


Fig. 2: Estimated (a) residential burning and (b) landfill fires

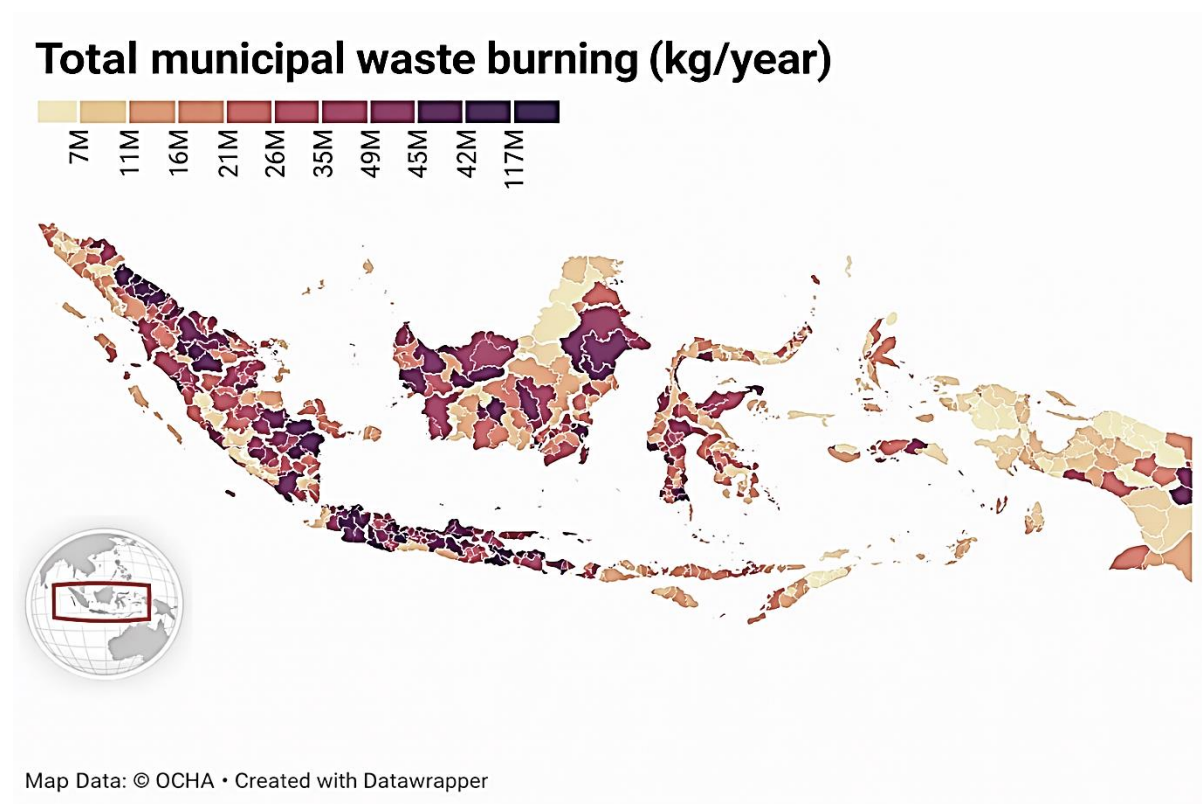


Fig. 3: Total waste burning incidents in Indonesia

This spatial concentration corresponds with regions noted for their high population density, significant municipal solid waste production, and ongoing deficiencies in efficient waste collection and treatment at the neighbourhood level. The continuity of high-intensity classes along Java's urban belt indicates that waste burning is not confined to isolated localities but represents a systemic challenge embedded within broader urban waste management dynamics (Guibrunet *et al.*, 2017). In Sumatra, the practice of burning waste reveals a more disjointed but nonetheless considerable pattern. Several districts in North Sumatra, South Sumatra, Riau, and Lampung fall within medium to high burning categories (approximately 35–77 Mkg/y), reflecting a combination of growing urban centres and semi-urban settlements with partial service coverage. Unlike Java, where high-intensity zones form contiguous clusters, Sumatra shows a patchwork

distribution, suggesting localized drivers such as uneven municipal services, differences in settlement density, and variable reliance on informal disposal practices (Ramaswami *et al.*, 2016). The regions of Kalimantan and Sulawesi display mainly moderate to low levels of waste burning intensity, with sporadic hotspots located near provincial capitals and fast-growing urban areas. These localized peaks indicate that waste burning is closely tied to urban growth nodes rather than widespread regional practices (Zaman *et al.*, 2011). In contrast, eastern Indonesia (Maluku and Papua) is dominated by lower intensity classes (generally <21 Mkg/year), consistent with lower population densities and smaller absolute waste generation. Nonetheless, the existence of dispersed moderate-intensity areas indicates that waste burning continues to be significant even in less populated regions, probably influenced by inadequate formal waste

management systems rather than the actual quantity of waste (Salim *et al.*, 2023). Overall, the map underscores that municipal waste burning in Indonesia is primarily a population- and urbanization-driven phenomenon, with the most severe burdens occurring in Java and major urban districts nationwide. The fine-scale spatial resolution highlights that mitigation strategies must move beyond provincial averages and instead target district-level hotspots, where interventions such as improved collection coverage, decentralized treatment, and behavioral change programs are likely to yield the greatest emission reductions (Thompson *et al.*, 2024). This spatial diversity highlights the importance of implementing place-specific waste management strategies, particularly in fast-developing urban corridors where the rise in waste production continually exceeds the expansion of infrastructure (Midha and Horne, 2024). Open waste burning contributes not only to national greenhouse gas emissions and long-term climate change, but also to immediate local environmental and health risks. Pollutants such as particulate matter (PM), carbon monoxide, and other combustion-related gases can degrade air quality in nearby communities, particularly in densely populated areas where burning occurs close to households. This study focuses on quantifying emissions primarily in relation to their climate impact (expressed in CO₂ equivalents), yet the concentration of high-burning regions implies that the exposure to localized air pollution may be considerable. Therefore, reducing OWB can provide both short-term local air quality benefits and long-term climate mitigation advantages.

Reasons of Household Burning Practices

The survey results (Table 5) indicate that the respondent pool was dominated by female participants, who accounted for 62.88 % (n = 454)

of the total valid responses, while male respondents represented 37.12 % (n = 268). This gender distribution indicates that the dataset significantly represents viewpoints from individuals who are frequently engaged in everyday household tasks, such as waste management and disposal choices. As such, the responses provide valuable insight into household-level waste management behaviors and perceptions relevant to residential OWB. Regarding educational qualifications, the participants were predominantly well educated, with the largest proportion holding a Bachelor's degree (42.80 %, n = 309), followed by senior high school or vocational education (39.89 %, n = 288). Smaller shares of respondents reported Diploma-level education (6.09 %) and Master's degree or higher (5.12 %), while respondents with only primary or junior high school education together accounted for less than 6.1 % of the sample. Notably, no respondents reported having no formal education. This educational profile suggests that the survey predominantly included participants who possess adequate literacy and awareness to offer informed feedback regarding waste management practices and perceived drivers of OWB. Regarding household roles and settlement characteristics, only 17.31 % (n = 125) of respondents identified themselves as heads of household, whereas the majority (82.69 %, n = 597) were non-head household members. This indicates that choices concerning waste management and incineration might not be determined exclusively by the heads of households, but are shaped by wider household interactions. Furthermore, most respondents resided in urban areas (78.67 %, n = 568), with 21.33 % (n = 154) living in rural settings. Given the higher representation of urban respondents, the survey results are interpreted as indicative of household experiences and are not used to claim

Table 5: Demographic profile of respondents

Gender	Total	Average
Male	268	37.12%
Female	454	62.88%
Highest level of education	Total	Average
No formal education	0	0.00%
Primary school	11	1.52%
Junior high school	33	4.57%
Senior high school / vocational high school	288	39.89%
Diploma	44	6.09%
Bachelor's degree	309	42.80%
Master's degree or higher	37	5.12%
Head of household	Total	Average
Yes	125	17.31%
No	597	82.69%
Living in urban / rural area	Total	Average
Urban	568	78.67%
Rural	154	21.33%

national prevalence estimates. The robust urban representation corresponds with the spatial analysis that indicates increased waste generation and burning intensity in urban and peri-urban areas, offering a significant demographic foundation for investigating the factors influencing residential OWB practices in Indonesia.

The waste management profile (Table 6) reveals substantial gaps between regulatory awareness, infrastructure availability, and actual household waste disposal practices. Although 41.27% (n = 298) of respondents reported being aware of regulations related to waste burning, a considerable proportion was either reported as not being aware (26.59%) or as not knowing about such regulations (32.13%). This suggests that over fifty percent of the participants do not possess a clear understanding of the current legal limitations regarding waste burning, indicating that regulatory frameworks have not been effectively conveyed or assimilated at the household level (Pathak et al., 2023). Participation in socialization or training activities related to waste management was reported by 57.20 % (n = 413) of respondents, while 42.80% (n = 309) had never participated in any formal waste-related

education or outreach. Despite this relatively high level of reported participation, the availability of supporting waste infrastructure remains limited. Only 20.97% (n = 250) of respondents indicated the presence of a waste bank in their neighborhood, while 44.74% reported that no waste bank was available and 20.64% were unsure. Furthermore, MRFs were only available to 18.84% (n = 136) of those surveyed, with nearly half (49.86%) indicating that such facilities were nonexistent in their locality, emphasizing the structural barriers that hinder effective waste diversion strategies. In terms of actual waste disposal practices, open burning remains the most prevalent method, reported by 30.03% (n = 358) of respondents. This exceeds the share of households served by community or private waste collectors (26.85 %) and municipal waste services (15.27%). Alternative disposal methods such as composting (12.25%) and burial (9.90%) were reported less frequently, while environmentally harmful practices such as disposing waste into rivers were reported by a small but notable fraction (2.85%). The minimal percentage of households contributing waste to waste banks (0.50%) highlights the restricted operational scope of material recovery systems (Budihardjo et al., 2022).

Table 6: Waste management profile

Awareness of regulations related to waste burning	Total	Average
Yes	298	41.27%
No	192	26.59%
Do not know	232	32.13%
Socialization / training on waste management	Total	Average
Ever participated	413	57.20%
Never participated	309	42.80%
Availability of a waste bank	Total	Average
Yes	250	20.97%
No	323	44.74%
Do not know	149	20.64%
Availability of material recovery facility	Total	Average
Yes	136	18.84%
No	360	49.86%
Do not know	226	31.30%
Waste disposal method	Total	Average
Collected by community/private waste collectors	320	26.85%
Collected by municipal waste services (Environmental Agency)	182	15.27%
Burned	358	30.03%
Disposed of into the river	34	2.85%
Buried	118	9.90%
Composted	146	12.25%
Disposed of at waste collection site (WCS)	28	2.35%
Collected to waste bank	6	0.50%
Amount of waste generated per day	Total	Average
< 2 L	13	1.80%
5-L waste bin	188	26.07%
10-L waste bin	240	33.29%
15-L waste bin	144	19.97%
20-L waste bin	130	18.03%
More than 20-L waste bin	6	0.83%

Regarding daily waste generation, most households reported moderate waste volumes, with 33.29% (n = 240) generating approximately one 10-liter (L) waste bin per day, followed by 26.07 % (n = 188) using 5-L bins and 19.97% (n = 144) reporting 15-L bins. Only 18.03% generated around 20 L/d, and less than 1% exceeded this amount. This distribution implies that the occurrence of open burning is not chiefly motivated by unusually elevated waste generation, but rather by inadequate access to collection services and treatment infrastructure, highlighting the importance of systemic and institutional factors in shaping residential OWB practices (Ramaswami *et al.*, 2016; Velis *et al.*, 2021). Fig. 4(a) presents the composition of household waste generated, based on questionnaire responses, while Fig. 4(b) shows the

composition of waste found in burned piles, reflecting materials that are preferentially subjected to residential burning. Food waste constitutes the largest portion of the generation profile at 33.68%, succeeded by thin-film plastics at 14.20%, backyard waste such as leaves and garden residues at 10.70%, rigid plastics at 9.85%, and paper and cardboard at 9.61%. Smaller fractions include wood (5.03 %), nappies (2.75 %), textiles, hazardous waste, rubber/leather, metals, and glass, each contributing less than 3 %. This distribution indicates that organic and low-density materials constitute the bulk of household waste streams, consistent with typical municipal waste profiles in Indonesia. Conversely, the structure of charred waste mounds (Fig. 4b) is distinctly different from the generation profile, underscoring selective combustion tendencies.

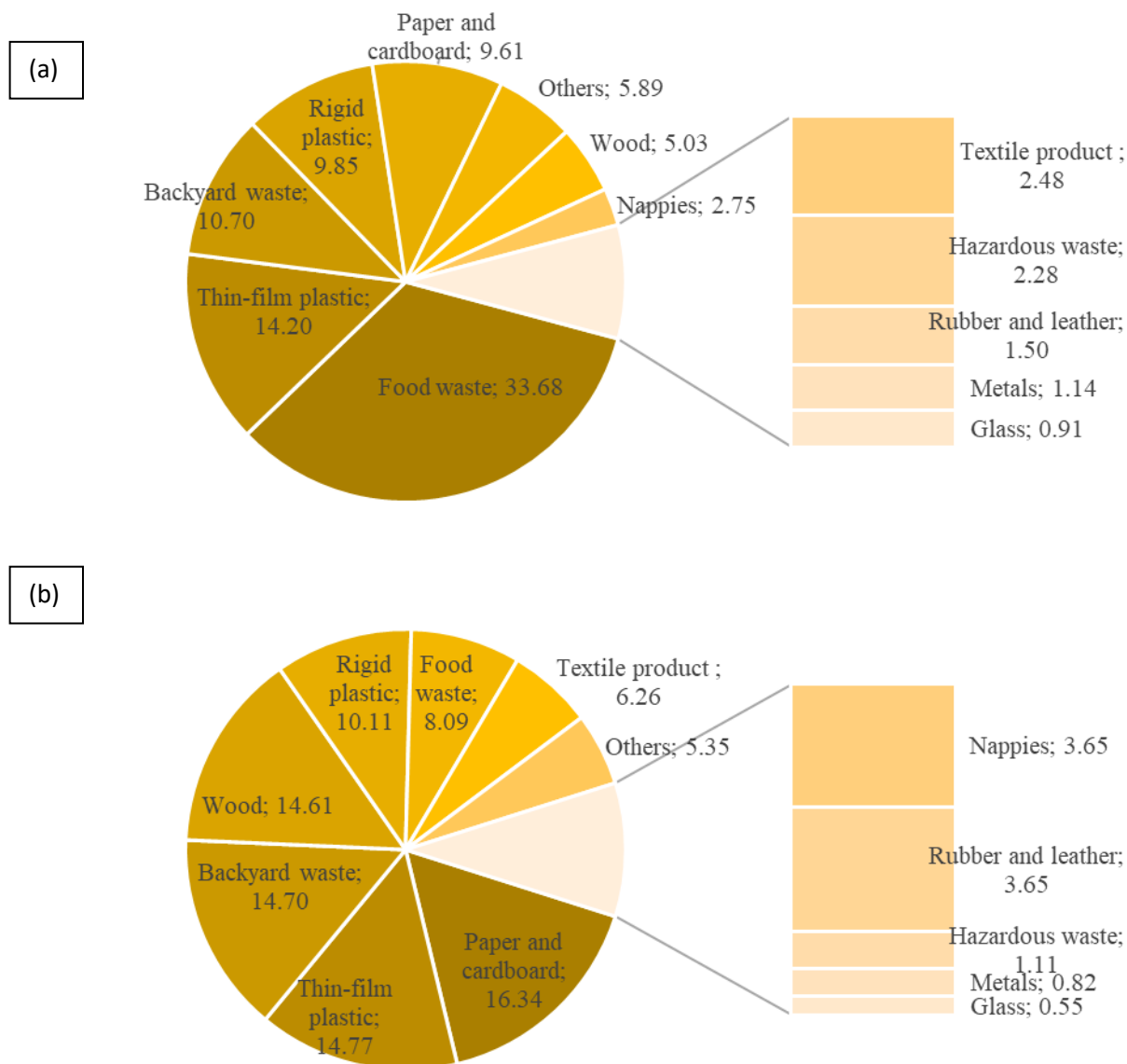


Fig. 4: (a) Percentage of waste generation; (b) percentage of waste found in burned piles based on questionnaire (%)

Paper and cardboard (16.34 %), thin-film plastics (14.77 %), backyard waste (14.70 %), and wood (14.61 %) collectively dominate burned materials, while food waste accounts for only 8.09 %. The diminished occurrence of food waste in incinerated piles indicates that moist organic materials are less prone to combustion, probably because of their elevated moisture levels and

reduced combustibility (Chavan *et al.*, 2022). Conversely, dry, combustible materials such as paper, plastics, and wood are disproportionately represented, indicating that households consciously or unconsciously select materials that are easier to ignite and burn efficiently (Ramadan *et al.*, 2022a; Ramadan *et al.*, 2023). The additional data sourced from the SIPSN website further

elucidates these findings within the context of the nation. According to SIPSN, food waste constitutes the largest share of municipal solid waste (40.45 %) in Indonesia, followed by plastics (19.23 %), wood and garden waste (12.43 %), and paper and cardboard (11.16 %). Non-combustible components, including metals (3.57 %) and glass (2.39 %), as well as textiles and rubber/leather, constitute relatively small proportions. The close alignment between the SIPSN composition and the questionnaire-based generation profile supports the representativeness of the survey data, while the divergence between generated and burned waste highlights a critical behavioral dimension of residential OWB (Ramadan *et al.*, 2022b). Furthermore, the findings suggest that the characteristics of the waste materials play a more significant role than the total amount of waste in determining the practice of burning residential waste. Although food waste dominates overall waste generation, it contributes far less to burned waste, whereas plastics, paper, and biomass residues are preferentially burned. This finding has important implications for mitigation strategies, suggesting that interventions targeting plastic reduction, paper recovery, and garden waste management may be more effective in reducing residential OWB than approaches focusing solely on organic waste treatment (Sharma *et al.*, 2024; Wang *et al.*, 2023).

Fig. 5 presents the results of the Latent Dirichlet Allocation analysis applied to open-ended questionnaire responses, revealing four dominant topics that explain the persistence of residential OWB practices. The average topic probability reflects the relative significance of each topic, demonstrating the frequency of the related narrative in the responses provided by participants (Buenano-Fernandez *et al.*, 2020). Topic prevalence reflects the respondent sample and was not weighted to adjust for demographic imbalance; therefore, the identified drivers should

be interpreted within the context of the survey profile. The highest-ranked topic (Topic 1) corresponds to insufficient waste collection systems and inadequate infrastructure, emphasizing the structural constraints faced by households. This topic constitutes the most significant portion of responses, suggesting that a considerable number of households engage in waste burning primarily due to the lack, irregularity, or limited accessibility of formal waste collection services, rather than a conscious choice to violate regulations. The second most prominent theme (Topic 3) relates to convenience and ease of waste elimination, where respondents described burning as the fastest and most practical method to remove accumulated waste. This finding suggests that OWB is perceived as a low-effort solution, particularly in contexts where waste separation, storage, or transport to collection points requires additional time or resources. Closely related but less dominant is Topic 2, which highlights the lack of fees, penalties, or enforcement mechanisms associated with burning practices. The comparatively lower status of this subject suggests that economic barriers and regulatory enforcement are of lesser importance when compared to infrastructure and convenience; however, their lack still plays a role in the persistence of OWB. The study did not measure enforcement capacity or penalties directly. However, responses indicate that weak monitoring and limited enforcement reduce the deterrent effect of regulations, especially where waste services are inadequate. The lowest-ranked topic (Topic 4) captures habitual behavior, perceptions, and cultural traditions, indicating that social norms and long-standing practices play a role but are not the primary drivers at the national scale. Despite being considered less significant than structural factors, this issue illustrates that in various communities, open burning is regarded as a habitual and socially accepted practice that has been carried out for

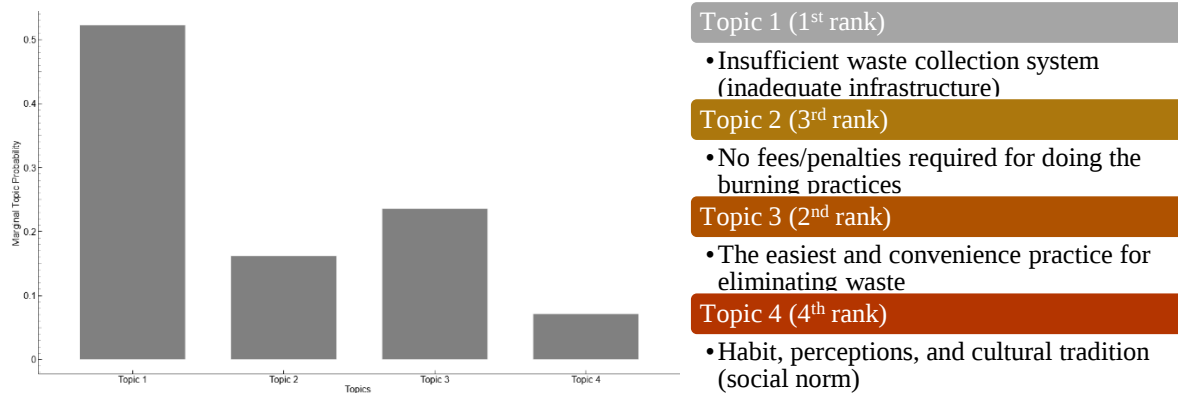


Fig. 5: Reason behind OWB practices

generations, particularly in locations where formal waste management services have historically been unavailable. This suggests that OWB in Indonesia is less a deeply entrenched cultural practice and more a pragmatic response to service gaps and daily household needs. Nevertheless, the persistence of habitual burning behavior indicates that infrastructure improvements alone may not fully eliminate OWB without parallel efforts to shift social norms and everyday household practices. Additional qualitative responses further support this interpretation, citing pest control, low perceived health and environmental risks, and limited awareness as reinforcing factors that sustain burning practices, even among respondents who are aware of alternative waste management options. While the survey lacked a comprehensive health risk perception scale, various responses suggest that the awareness of environmental and health effects is inconsistent. A considerable proportion of respondents reported limited knowledge of regulatory restrictions, and qualitative answers suggest that some households underestimate the health risks associated with smoke exposure. This indicates that insufficient risk awareness may contribute to the persistence of OWB alongside structural constraints. The findings from the LDA indicate that the residential OWB in Indonesia is primarily influenced by

structural and practical elements, instead of cultural connections or intentional breaches of regulations. These findings reinforce the need for interventions that prioritize improving waste collection coverage and service reliability, alongside targeted awareness-raising and enforcement measures, to effectively reduce OWB practices at the household level (Etim *et al.*, 2024).

Strategy to reduce OWB practices

Fig. 6 summarizes the dominant strategies for reducing residential OWB as identified through LDA analysis of respondents' open-ended suggestions. The highest-ranked topic (Topic 1) emphasizes the need to improve reliable and affordable waste collection and treatment infrastructure, indicating that respondents perceive structural service improvements as the most effective intervention. This discovery supports previous findings that indicate insufficient collection coverage and restricted access to formal waste management facilities are the main factors contributing to OWB (Chaudhary *et al.*, 2021; Ramaswami *et al.*, 2016). The prominence of this topic suggests that behavioral change alone is insufficient in the absence of accessible and dependable waste services, particularly in densely populated and peri-urban

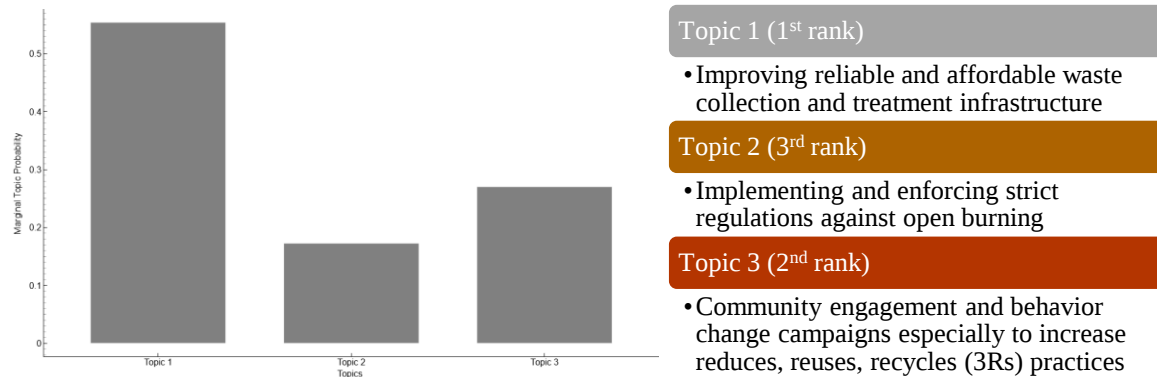


Fig. 6: Strategy to reduce OWB

areas. This outcome also indicates a disparity between the current national waste management regulations and their actual execution at the local level. Although Indonesia has established policy targets to reduce unmanaged waste and improve collection coverage, uneven infrastructure development and limited municipal capacity continue to constrain enforcement and service delivery. Consequently, households may choose open burning not from a lack of regulatory measures, but due to the absence of practical and affordable alternatives. The second most influential theme (Topic 3) highlights the importance of community engagement and behavior change campaigns, with a particular focus on strengthening reduce, reuse, and recycle (3Rs) practices. Participants consistently highlighted the importance of ongoing education, community involvement, and local leadership to promote source separation and waste minimization (Afnan *et al.*, 2025; Alimoradiyan *et al.*, 2024). The relatively high ranking of this topic indicates recognition that infrastructure improvements must be accompanied by social interventions that reshape everyday waste handling practices and perceptions, especially in households that currently rely on burning for convenience. In contrast, Topic 2, which focuses on implementing and enforcing stricter regulations against open burning, was ranked

third. This indicates that although regulatory measures are recognized as essential, their effectiveness is viewed as diminished when applied independently (Wonkka *et al.*, 2015). Respondents implicitly recognized that enforcement without viable alternatives may be difficult to sustain and could disproportionately affect households lacking access to waste services. Taken together, the LDA results indicate that an effective OWB reduction strategy in Indonesia requires a sequenced and integrated approach, prioritizing infrastructure provision, reinforced by community engagement, and supported by consistent regulatory enforcement. This indicates that although regulatory measures are recognized as essential, their effectiveness is viewed as diminished when applied independently (Afnan *et al.*, 2025). Several studies and pilot initiatives in Indonesia and other low- and middle-income countries have demonstrated that improved waste collection coverage and community-based waste management programs can significantly reduce open burning practices. For example, community-led waste bank initiatives and expanded door-to-door collection services have been associated with reduced informal disposal and burning in peri-urban settlements (Velis *et al.*, 2021; Afnan *et al.*, 2025). These cases suggest that when reliable collection systems are combined with local engagement and awareness campaigns,

households are more likely to shift away from open burning toward formal disposal pathways. Although this study does not evaluate specific pilot projects quantitatively, existing evidence supports the feasibility of infrastructure and community-driven interventions as effective OWB reduction strategies. To assess the effectiveness of these interventions, it is essential to have clear and measurable indicators. These may include a reduction in the estimated amount of waste burned (Mt per year), lower OWB-related emissions (MtCO₂e), increased waste collection coverage (percentage of households served), higher participation in recycling or waste bank programs, and improved awareness of waste regulations. At the community level, a reduction in the reported instances of burning practices and improved waste separation may also signify advancement. Tracking these indicators over time will help evaluate whether the interventions are effective. Reducing open waste burning can also support Indonesia's Nationally Determined Contributions (NDCs). Since OWB produces greenhouse gas emissions, lowering this practice can help reduce national emissions and support the country's climate targets.

CONCLUSION

This study provides a comprehensive national assessment of residential OWB in Indonesia by integrating national datasets, a large-scale household survey, spatial analysis, and machine learning-based text analytics. By combining activity and emission inventory methods with village–city classifications obtained from official statistics, this study enhances prior methodologies and provides a more context-aware assessment of waste burning activities. The refinement introduced in this study specifically lies in the application of official village–city administrative classifications to improve the allocation of uncollected waste fractions and enhance spatial resolution compared with generalized rural–urban

assumptions. The results indicate that approximately 26.6 Mt of municipal waste are openly burned annually, resulting in an estimated 23.3 MtCO₂e of climate impact, with residential burning accounting for around 70% of total waste burned, substantially exceeding contributions from landfill fires. Spatial analysis reveals that OWB distributed unevenly, with Java Island accounting for the majority of national totals due to its high population density and significant absolute waste generation. Meanwhile, certain provinces in Sumatra and Sulawesi are identified as secondary hotspots. At finer administrative scales, district-level mapping highlights strong intra-provincial heterogeneity, underscoring the limitations of province-level averages for policy design. The analysis of the composition of waste generation in comparison to that of burned waste illustrates that OWB is a selective process. It shows that and combustible materials such as plastics, paper, wood, and garden waste disproportionately represented in burned piles, despite food waste dominating overall waste generation. The examination of waste generation composition relative to the survey results on burned waste, combined with topic modeling analysis, yields significant understanding of the core drivers of OWB. The dominant reasons for continued burning are structural and practical, particularly insufficient waste collection services and infrastructure, followed by convenience and weak enforcement. Cultural norms and habitual behavior play a secondary role. However, given the descriptive and inventory-based scope of the study and the higher representation of urban respondents in the survey, these findings reflect reported patterns and spatial associations rather than statistically verified causal relationships at the national level. Furthermore, the strategies aimed at reducing OWB focus on bolstering reliable and affordable waste collection and treatment systems, alongside community engagement and initiatives for behavior modification. Regulatory enforcement, on the

other hand, is less impactful without the presence of service provision. These findings highlight that OWB is largely a response to systemic gaps rather than intentional non-compliance. Overall, the study demonstrates that effective reduction of residential OWB in Indonesia requires a hierarchical and integrated policy approach. Priority should be placed on enhancing and stabilizing waste collection coverage, especially in urban and peri-urban hotspots, while also implementing targeted measures for combustible waste fractions. Community-based programs promoting waste reduction and segregation should be strengthened to support infrastructure investments, while enforcement mechanisms should be applied in a supportive and context-aware manner. It is essential to point out that the emission estimates outlined in this study are deterministic central values obtained from existing national datasets and literature-based emission factors. An analysis of uncertainty propagation in a formal context, as well as scenario-based modeling of potential reductions in emissions under better collection coverage were not conducted. Therefore, the reported values should be interpreted as indicative national scale estimates rather than precise measurements with quantified confidence intervals. Future research incorporating uncertainty analysis and mitigation scenario modelling would strengthen the quantitative basis for policy evaluation. By linking household behavior, spatial patterns, and emission impacts, this study provides an evidence-based foundation for designing targeted OWB mitigation strategies and contributes to national efforts to reduce air pollution and climate impacts from unmanaged waste.

AUTHOR CONTRIBUTIONS

B.S. Ramadan Conceptualization, validation, funding acquisition, and writing – original draft; S. Sendari Conceptualization, data curation, writing, review and editing, visualization; B. Ratnawati Visualization, project administration, software;

A.D. Sakti Methodology, validation, resources; A.T. Balasbaneh Validation, software, methodology; M.A. Budihardjo formal analysis, project administration; T. Matsumoto Supervision, resources; A.S. Puspita Writing – original draft, validation, resources.

ACKNOWLEDGEMENTS

The authors would like to express their deepest gratitude to Universitas Diponegoro, which funded the research under the Riset Kolaborasi Indonesia scheme number [442-06/UN7.D2/PP/IV/2024].

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
λ	The proportion of waste at a dumpsite that is burned
δ	The fraction of combustible MSW
<	Less than
3Rs	Reduce, Reuse, Recycle
BC	Black carbon
B_{frac}	Carbon conversion fraction
BPS	Indonesian Statistical Agency
CF_j	The total carbon fractions
CH_4	Methane
CO	Carbon Monoxide
CO ₂	Carbon dioxide
CO _{2T}	Total CO ₂ emissions
CSV	Comma-Separated Values
DKI	Daerah Khusus Ibukota
DLH	Dinas Lingkungan Hidup
dm_j	Dry matter
EF	Emission factor
EF_{CH_4}	Emission factor for methane
FCF_j	The total fossil carbon fraction
$F_{uncollected(rural)}$	Fraction of uncollected waste (rural)
$F_{uncollected(urban)}$	Fraction of uncollected waste (urban)
GRDP	Gross Regional Domestic Product

GWP_x	Global Warming Potential of pollutant x
IPCC	Intergovernmental Panel on Climate Change
kg/d	Kilogram per day
kg/y	Kilogram per year
km ²	Square kilometres
L	Litre
L/d	Litres per day
LDA	Latent Dirichlet Allocation
LDavis	Latent Dirichlet Allocation Visualization
MDS	Multidimensional Scaling
MRF	Material Recovery Facility
MSW	Municipal Solid Waste
MSW_p	Municipal Solid Waste generated
Mt	Million tonnes
Mt/y	Million tonnes per year
MtCO _{2e}	Million tonnes of carbon dioxide equivalent
NO _x	Nitrogen Oxides (NO dan NO ₂)
N ₂ O	Nitrous Oxide
OWB	Open Waste Burning
PM _{2.5}	Particulate Matter ≤2.5 µm
PM ₁₀	Particulate Matter ≤10 µm
P_{rural}	Rural population
P_{urban}	Urban population
Rp	Indonesian Rupiah
SIPSN	National Waste Management Information System
SO ₂	Sulfur Dioxide
t	Tonne
t/y	Tonnes per year
tCO _{2e}	Tonne CO ₂ equivalent
W_B	Waste burning total
W_{Bdump}	Waste burning at disposal sites
W_{Bres}	Residential waste burning
WCS	Waste Collection Site
WF_j	The fraction of waste type/material of component j in the MSW

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HOW TO CITE THIS ARTICLE

Ramadan, B.S.; Sendari, S.; Ratnawati, B.; Sakti, A.D.; Balasbaneh, A.T.; Budihardjo, M.A.; Matsumoto, T.; Puspita, A.S., (2026). An extensive inventory of municipal waste incineration nationwide based on machine learning analysis. *Global J. Environ. Sci. Manage.*, 12(2): 745-770.

DOI: [10.22034/gjesm.2026.02.14](https://doi.org/10.22034/gjesm.2026.02.14)

URL: https://www.gjesm.net/article_734919.html

